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HARDWARE-IN-THE-LOOP POWER EXTRACTION USING DIFFERENT REAL-TIME PLATFORMS (POSTPRINT)

Michael Boyd, John McNichols, Mitch Wolff, Michael Corbett, and Peter Lamm

PC Krause and Associates, Inc.

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14. ABSTRACT
Aircraft power demands continue to increase with the increase in electrical subsystems. These subsystems directly affect the behavior of the power and propulsion systems and can no longer be neglected or assumed linear in system analyses. The complex models designed to integrate new capabilities have a high computational cost. Hardware-in-the-loop (HIL) is being used to investigate aircraft power systems by suing a combination of hardware and simulations. This paper considers three different real-time simulators in the same HIL configuration. A representative electrical power system is removed from a turbine engine simulation and is replaced with the appropriate hardware attached to a 350 horsepower drive stand. Variables are passed between the hardware and the simulation in real-0time to update model parameters and to synchronize the hardware with the model. Real-time simulation platforms from dSPACE, National Instruments (NI), and the MathWorks' xPC are utilized for this investigation. Similar results are obtained when using HIL and a simulated load. Initially, noticeable differences are seen when comparing the results.

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Hardware-in-the-Loop Power Extraction Using Different Real-Time Platforms

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ABSTRACT

Aircraft power demands continue to increase with the increase in electrical subsystems. These subsystems directly affect the behavior of the power and propulsion systems and can no longer be neglected or assumed linear in system analyses. The complex models designed to integrate new capabilities have a high computational cost. Hardware-in-the-loop (HIL) is being used to investigate aircraft power systems by using a combination of hardware and simulations. This paper considers three different real-time simulators in the same HIL configuration. A representative electrical power system is removed from a turbine engine simulation and is replaced with the appropriate hardware attached to a 350 horsepower drive stand. Variables are passed between the hardware and the simulation in real-time to update model parameters and to synchronize the hardware with the model. Real-time simulation platforms from dSPACE, National Instruments (NI), and The MathWorks' xPC are utilized for this investigation. Similar results are obtained when using HIL and a simulated load. Initially, noticeable differences are seen when comparing the results from each real-time operating system. However, discrepancies in test results obtained from the NI system can be resolved. This paper briefly details the underlying problem and its solution before discussing test results which show that dSPACE, NI, and xPC can be configured to match the baseline Simulink data.

INTRODUCTION

As a result of the new high-power capabilities being considered for aircraft, the potential for non-linear interactions between propulsion, power and thermal systems has arisen. Historically, such interactions were minimal and were neglected or assumed linear for integrated system analyses. Advanced modeling and simulation techniques are required to study these non-linear interactions and their system-level consequences.

These increased power and thermal loads introduce large-scale dynamics that affect the entire aircraft. The high-power, low-efficiency loads introduce voltage transients that jeopardize electrical power quality and introduce large heat loads that encroach upon fuel temperature or component limits. Also, snap turbine engine power take-offs increase risks of engine stall, high mechanical stress, shaft breaks, and reduced thrust.

For advanced capabilities wherein the subsystem interactions are tightly coupled and no longer merely perturbational, the design and analysis must be performed at a high level to obtain a system-level power optimized aircraft. This type of integrated design and analysis will not only optimize performance, cost, weight, and volume but is essential if such advanced capabilities are to become feasible. Therefore, a computationally-efficient multi-physics system simulation must be utilized to address issues such as electric actuator power regeneration, fuel circulation for improved thermal management, and interactions between shaft power extraction and aircraft capabilities (speed, altitude, and maneuverability).

In this paper, the power and propulsion systems were exercised using electrical shaft power extractions from both the high pressure (HP) and low pressure (LP) spools. Although the size of the power and thermal loads considered in this paper may be smaller than would be required for a military aircraft, these issues are conceptually similar since electrical shaft loading is a large percentage of the available turbine engine shaft power at high altitudes. Advanced integrated architectures were evaluated from a system-level perspective and compared with state of the art modeling and simulation methods in terms of power quality, stall margin, and shaft speed.

Next generation aircraft requirements demand improved dynamic performance, power availability, emissions, reliability, and operability compared to present designs. To meet these requirements, preliminary design tools are

needed that accurately model the transient phenomena of the power system. Recently, significant progress has been made in transient engine modeling utilizing MATLAB/Simulink™.[1,2] These dynamic models surpass the capabilities of traditional “cycle deck” performance models by considering time domain interactions of various components within the turbine engine. Using additional time-domain models allows a transient engine model to interface with other aircraft subsystems as it would in an actual implementation. A power take-off generator and a full authority digital engine control (FADEC) are coupled to the transient engine model for the tests presented in this paper.

TRANSIENT TURBINE ENGINE MODELING

A generic turbine engine model in MATLAB/Simulink, which has not been validated with detailed experimental data, was utilized for this investigation. This model was based upon the work done by Gastineau, and a lumped component approach was used for ease of modification and replacement of engine components[4]. Each component was created with its own set of inputs and outputs, and was based on fundamental laws of physics such as the conservation of mass, momentum, and energy. In addition, gas tables were used to calculate properties such as enthalpy and specific heat for pure air or the fuel-air mixture as a function of temperature, pressure, and fuel-air ratio.

A multi-stage turbine or compressor was simulated as a single component. This approach was adopted because turbine and compressor maps are generally created in a lumped fashion and not stage-by-stage. Similarly, the combustor simulated combustion of a lumped amount of fuel and air in a control volume. It did not simulate the flame distribution or flame dynamics of the combustion process. This lumped, zero-dimensional approach is sufficient to capture the dynamics of interest for system integration studies.

The engine modeled in this paper was a two spool turbofan engine with the specifications shown in Table 1. A key feature of the Air Force Research Laboratory (AFRL) generic engine model is its ability to simulate transient conditions. Transient simulation, in addition to steady state analysis, is vital in the design, testing, and analysis of turbine engines. Dynamic system simulations capture overshoot characteristics of a turbine engine which could actually cause the engine to fail even though a steady state analysis might suggest stability.

Specification	Value
Number of spools	2
Bypass ratio	4.9
LP spool design speed	8700 rpm
HP spool design speed	14,700 rpm
Altitude design	65,000 ft
Max altitude	70,000 ft
Mach number design	0.65
Max Mach number	0.65
Afterburner	None
Max steady state T4	3000 R

Table 1: Engine Design Specifications[5]

The AFRL generic turbine engine model has been designed to be flexible. The component maps and engine layout can easily be changed to model various engine types. The controller that was used can also be modified or replaced as appropriate. In its current configuration, the generic turbine engine model’s FADEC runs primarily on a fan speed limiter based on throttle setting. Different operating points can be specified by the user to examine the performance of the turbine engine by specifying parameters such as: deviation in ambient temperature from standard day temperature, HP and LP shaft loading, throttle lever angle (TLA), altitude, and Mach number. Although the model allows the user to record any variable, this paper focuses on the LP and HP spool speed, power load on the LP and HP spools, and HPC (high pressure compressor) surge margin.

This model’s level of complexity causes it to run about two times slower than real-time when using the *ode23t (Mod. Stiff/Trapezoidal)* variable step solver on a 2.0 GHz PC with 512 MB RAM and even slower yet when using the *ode4 (Runge-Kutta)* fixed-step solver and a 1 ms time step. To run the simulation in real-time, three platforms were tested: dSPACE, National Instruments’ (NI) LabVIEW Real-Time 8.5.1, and The MathWorks’ xPC Target. For the three real-time environments tested, the engine and FADEC were run together in a single simulation running on a single processor. The required convergence window for each model was 1 ms (the fixed simulation time step). The convergence time of the model on each system was well within the required window, suggesting that any of the real-time systems would support more complicated models than the one used in these tests.

It is important to note that in order to produce accurate results using National Instruments’ LabVIEW Real-Time, a workaround must be used to bypass an acknowledged software bug. Without the workaround, the NI real-time system produced inaccuracies in the results, most notably during transients, when compared to results obtained from the generic engine model running the same test in native Simulink (which is considered the “correct” data). The workaround consists of changing the “Tasking mode for periodic sample times” setting in the Simulink model’s configuration parameters prior to

building the model as a Dynamic Link Library (DLL) with Real-Time Workshop. By default, this is set to “Auto” which allows the multi-rate model (engine and FADEC have different sample times) to attempt to use multi-tasking. Apparently, this is not handled properly by the NI real-time scheduler and should be changed to “Single-Tasking” to ensure accuracy when running on the NI platform. Results are presented with both settings to properly document this phenomenon.

The Simulink environment of the AFRL generic engine model facilitated a relatively smooth transition to each real-time environment using Real-Time Workshop along with software from each vendor. For the HIL configuration, variables within the simulation were mapped to hardware controls and feedback sensors using digital-to-analog converters (DAC) and analog-to-digital converters (ADC), respectively. In this study, LP spool speed was the primary parameter passed from the model to the 350 horsepower motor/generator drive stand. This model variable was converted to an analog voltage (0-10 V) which corresponded (linearly) to a speed control for the drive stand.

The drive stand was thus controlled by the real-time simulation to emulate the LP spool of a turbine engine, and was connected to an electrical power system implemented in hardware. This electrical power system included a generator, its generator control unit (GCU), and a resistor load bank. By switching on resistors in the load bank, an electromagnetic resistance (torque) was applied to the shaft by the generator. This was measured with a torque transducer and was fed back into the simulation. This LP shaft torque induced by the generator was used in the summation of shaft torques block within the model where it was subtracted (along with fan hub and fan tip torques) from the LP turbine torque output. The result was used to calculate a new LP shaft speed which was then commanded to the drive stand. The drive stand itself was physically capable of speeds up to 10,000 rpm, but the speed during testing was limited by the generator to approximately 8700 rpm. Ramalingam *et. al* demonstrated that the drive stand speed (as measured by a speed transducer) was able to track the model’s LP spool speed.[6]

To test each of the real-time simulators, several integrated engine/power tests were performed. Some tests used an altitude of 60,000 ft, a Mach number of 0.6, and a TLA of 91%; others used an altitude of 65,000 ft, a Mach number of 0.55, and a TLA of 95%. Unless specified otherwise, the NI system used the “Single-Tasking” fix.

TESTING AND ANALYSIS

The first series of tests was designed to show that the HIL system accurately matches the “Sim Only” data (where the LP load was applied as an idealized step function within the simulation) for dSPACE, NI, and xPC. A step load of 74.4 kW on the LP spool was used for this demonstration. Altitude, Mach number, and TLA were all held constant at 65,000 ft, 0.55, and 95%, respectively. In addition, a constant 10 kW load was applied to the HP spool in simulation. Figures 1 through 6 show the results of these tests. Figure 1 shows the LP spool speed as a function of time for both the NI Sim Only and HIL configurations, with the corresponding HPC surge margin shown in Figure 2. Figure 3 shows the LP spool speed versus time for both dSPACE configurations (HIL and simulation only), with the HP spool speed for the same test plotted in Figure 4. Figure 5 shows the LP spool speed results from the xPC Sim Only and HIL tests and Figure 6 shows the thrust results of the same test.

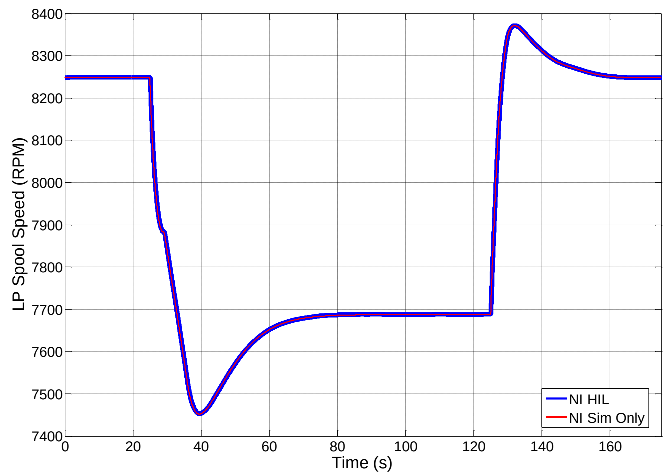


Figure 1: LP Spool Speed vs. Time – Comparison of HIL and Sim Only data from NI LabVIEW for a constant 10 kW HP load with a 74.4 kW step LP load.

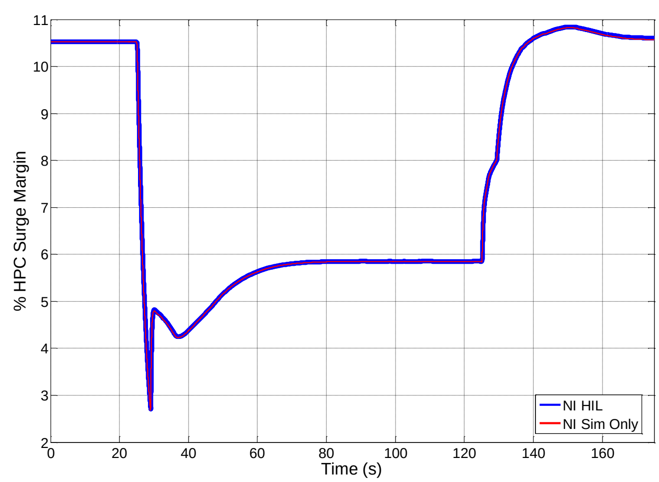


Figure 2: HPC Surge Margin vs. Time – Comparison of HIL and Sim Only data from NI LabVIEW for a constant 10 kW HP load with a 74.4 kW step LP load.

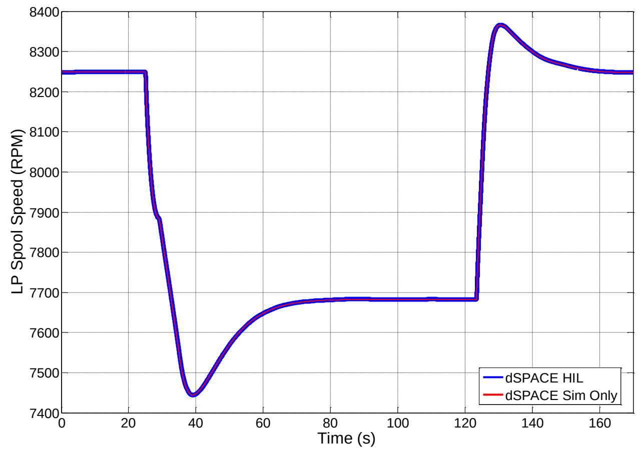


Figure 3: LP Spool Speed vs. Time – Comparison of HIL and Sim Only data from dSPACE for a constant 10 kW HP load with a 74.4 kW step LP load.

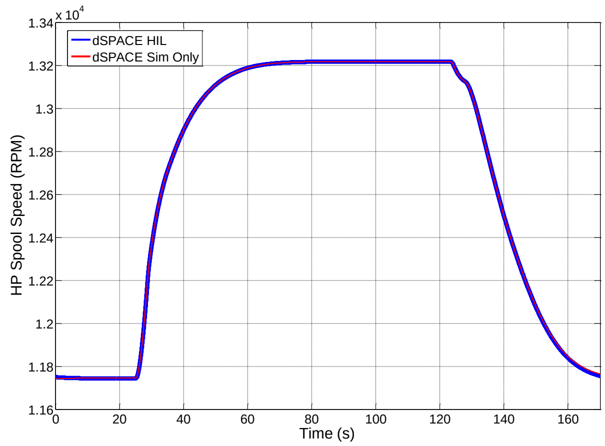


Figure 4: HP Spool Speed vs. Time – Comparison of HIL and Sim Only data from dSPACE for a constant 10 kW HP load with a 74.4 kW step LP load.

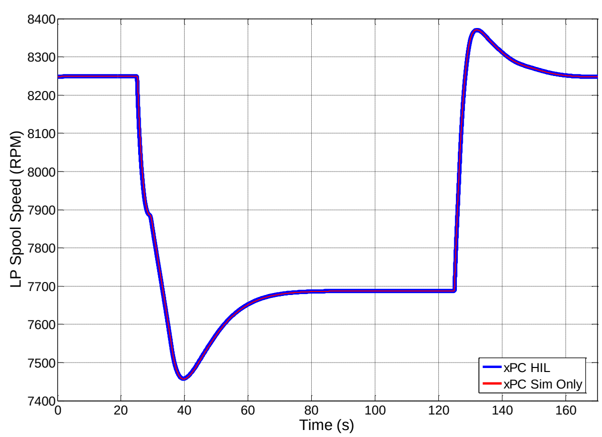


Figure 5: LP Spool Speed vs. Time – Comparison of HIL and Sim Only data from xPC for a constant 10 kW HP load with a 74.4 kW step LP load.

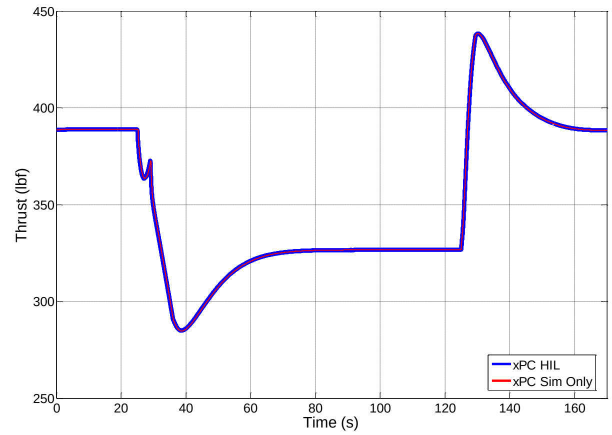


Figure 6: Thrust vs. Time – Comparison of HIL and Sim Only data from xPC for a constant 10 kW HP load with a 74.4 kW step LP load.

An engine cycle deck analysis for this test would only find the three steady state values (before the LP load is applied, with the LP load on, and after the LP load is removed) in each of Figures 1 through 6. With the ability to consider transient responses, the system is able to capture the dangerously low surge margin and possible stall which occurs between steady states (Figure 2). The large transient in LP spool speed (Figures 1, 3, and 5) could cause power quality concerns or reduced thrust as shown in Figure 6. In this test the FADEC is enforcing a turbine inlet temperature limit, which is why the LP spool speed does not recover to its target speed while the LP load is applied (Figures 1, 3, and 5). Each figure demonstrates excellent agreement between testing using a simulated LP load and a HIL LP load. Excellent agreement is also shown between HIL and Sim Only data sets for several other tests not presented in this paper. For this reason, HIL presents the ideal platform to consider both engine dynamics and electrical power quality (which is captured by the actual hardware response) during step loading of the LP spool.

Another series of tests was designed to compare the results between real-time systems during transient testing. In the first of these tests, a step load of 54.9 kW was put on the LP spool. All other variables were held constant: an altitude of 65,000 ft, Mach number of 0.55, and 95% TLA were used with a constant 10 kW load on the HP spool. To avoid uncertainty due to the generator hardware, this set of tests was conducted using the NI Simulation Only, dSPACE Simulation Only, and xPC Simulation Only modes. Figure 7 shows the LP spool speed versus time. Once again, as with Figures 1, 3, and 5, the FADEC limits the fuel flow due to a turbine inlet temperature limit and the LP spool is unable to return to its target speed. dSPACE, NI, and xPC show good agreement for this test, with no apparent deviation during either of the transients or steady state points. Figure 8 shows the HPC surge margin as a function of time corresponding to the same test as Figure 7. As was seen in Figure 7, dSPACE, NI, xPC are in agreement for this parameter, with no apparent discrepancies between the systems.

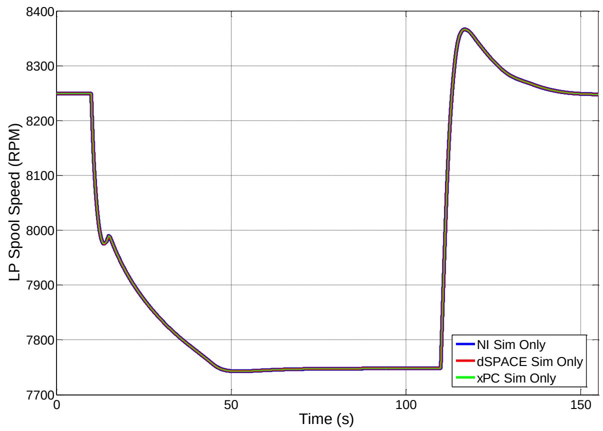


Figure 7: LP Spool Speed vs. Time – Comparison of NI, dSPACE, and xPC for a constant 10 kW HP load with a 59.4 kW step LP load.

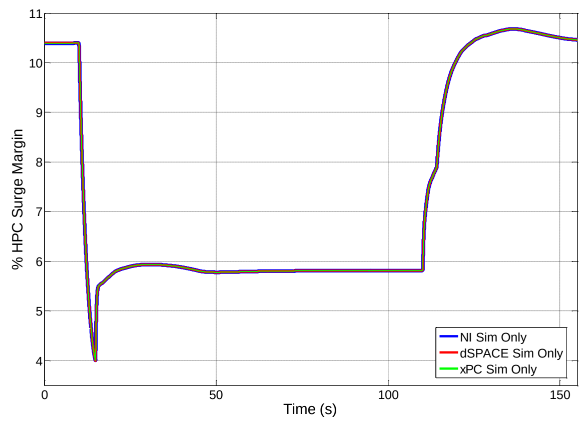


Figure 8: HPC Surge Margin vs. Time – Comparison of NI, dSPACE, and xPC for a constant 10 kW HP load with a 59.4 kW step LP load.

The next test in the series features the same 54.9 kW LP step load as the previous test. However, the constant operating conditions changed to an altitude of 60,000 ft, a Mach number of 0.6, and a 91% TLA. In addition, there was a constant 15 kW load on the HP spool for this test. Figure 9 shows the LP spool speed versus time.

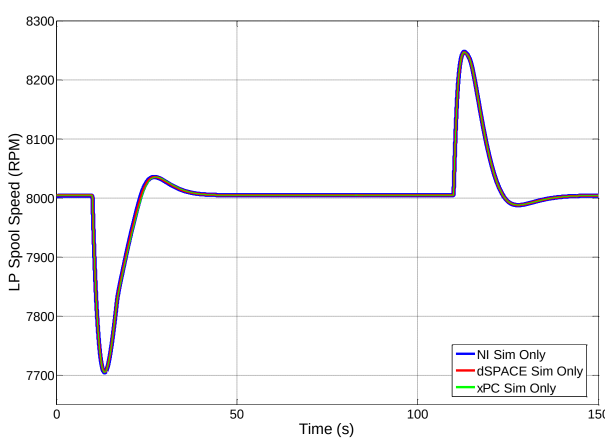


Figure 9: LP Spool Speed vs. Time – Comparison of NI, dSPACE, and xPC for a constant 15 kW HP load with a 59.4 kW step LP load.

Unlike in Figures 1, 3, and 5, the FADEC is not in a temperature limited control loop in this test. Therefore, the LP spool is able to fully recover to its target speed at the load-on steady state. Figure 9 shows NI, dSPACE, and xPC in excellent agreement for this test using Simulation Only datasets. Figure 10 shows the corresponding HP spool speed for this test.

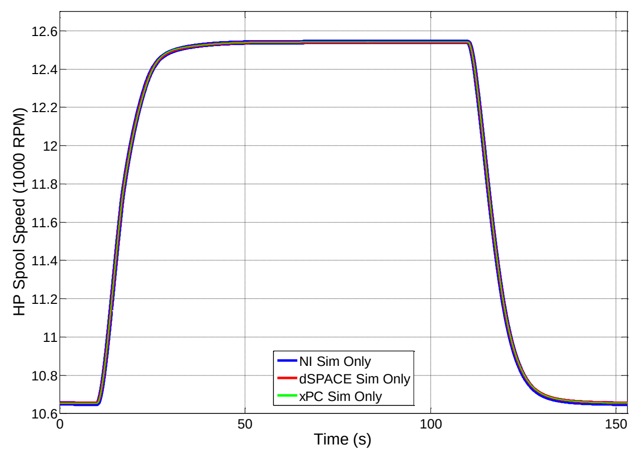


Figure 10: HP Spool Speed vs. Time – Comparison of NI, dSPACE, xPC for a constant 15 kW HP load with a 59.4 kW step LP load.

Like Figure 9, Figure 10 shows good agreement between dSPACE, NI and xPC, suggesting that any of the real-time simulators are capable of accurately running the dynamic engine model.

The hardware-in-the-loop tests demonstrate excellent matching using the same parameters as the corresponding simulation only test. The results can be seen below in Figure 11. The close agreement of the three systems shows that each system is capable of accurately running the engine model in real-time.

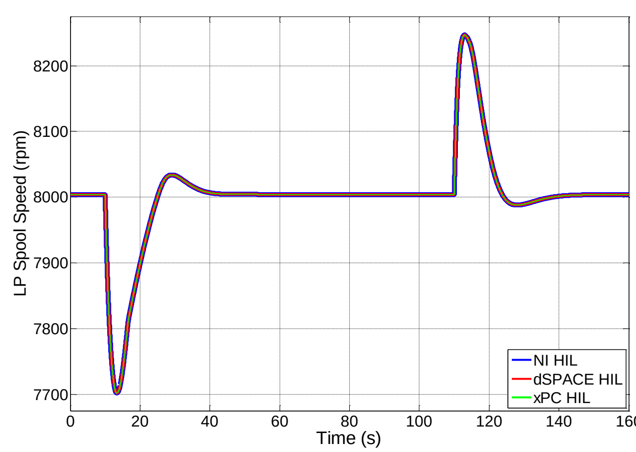


Figure 11: LP Spool Speed vs. Time – Comparison of NI, dSPACE, and xPC for a constant 15 kW HP load with a 59.4 kW step LP load.

While Figures 1 through 11 suggests that each of the real-time systems produces accurate results compared to the same model running in native Simulink, this was only the case after "fixing" the model running on NI. To demonstrate the problem, a test was run with a 74.4kW LP step load and all other variables are held constant: an altitude of 60,000 ft, a Mach number of 0.6, and a 91% TLA with a constant 15 kW load on the HP spool. Figure 12 shows the LP spool speed versus time. It uses the "Auto" tasking mode (which becomes "Multi-Tasking") mode in its Simulink setup.

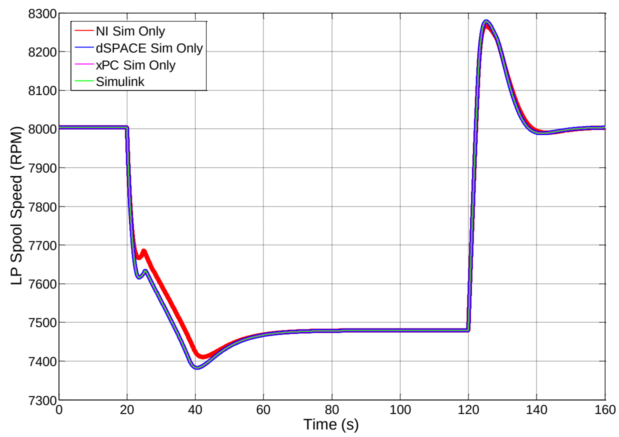
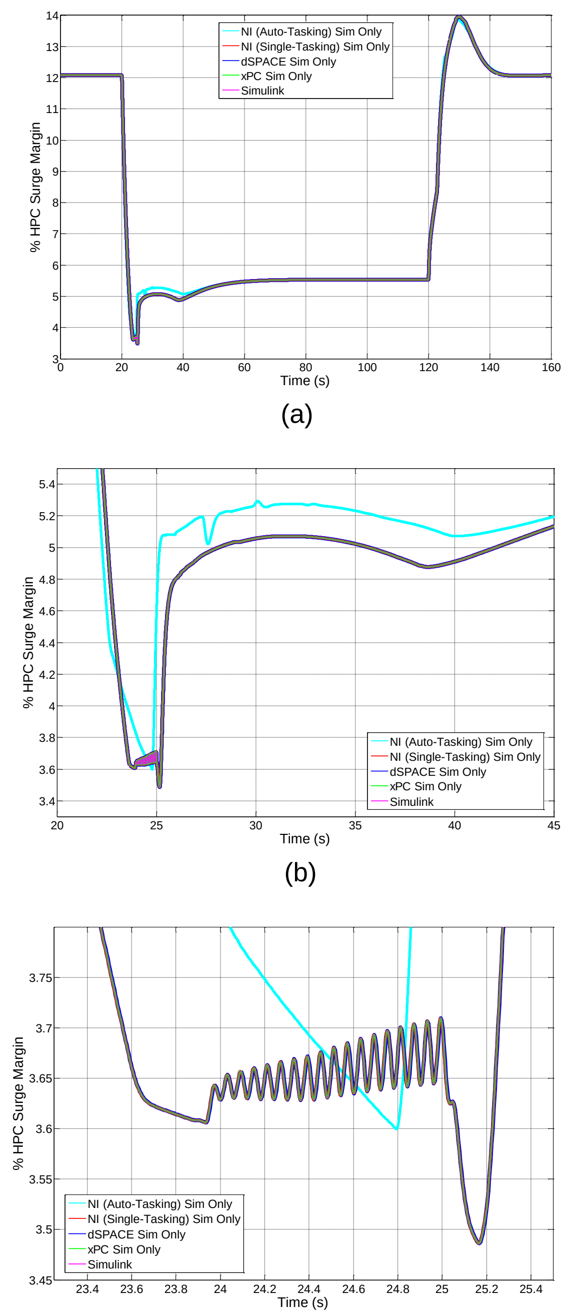


Figure 12: LP Spool Speed vs. Time – Comparison of NI, dSPACE, and xPC to native Simulink for a constant 15 kW HP load with a 74.4 kW step LP load.

As in Figures 1, 3, and 5, the FADEC enforces turbine temperature limits and the LP spool cannot recover to its target speed. dSPACE and xPC are in excellent agreement with the results obtained from Simulink and NI has the same steady state speeds. However, NI is noticeably off during the load-on transients. Considering other variables further illustrates the inability of the NI real-time scheduler to properly handle "Multi-Tasking" Simulink models.

Figure 13 shows the HPC surge margin versus time for the same test shown in Figure 11 and is used to showcase both the error of the "Multi-Tasking" model when running on NI and the accuracy of results obtained from the NI system when forcing the "Single-Tasking" option. Figure 13a shows that all data sets are in agreement except for the NI data set using auto-tasking. Figure 13b shows the same HPC surge margin plot, but is focused on the load-on transient which displays the discrepancy prominently. Figure 13c shows the same data again, but is zoomed in even further, specifically focused on the minimum surge margin and ringing phenomenon seen in the other four data sets. While all steady state values, the load-off transient, and the minimum surge margin value are very close for all four data sets, there is a drastic difference in the shape of the load-on transient between NI with "Auto" tasking mode (which converts to "Multi-Tasking" when built) and Simulink. The Simulink model shows oscillations in the HPC surge margin near its minimum during the load-on transient (Figure 13c). While dSPACE and xPC accurately replicates this trend, the NI system using "Multi-Tasking" shows no oscillations of any kind and instead shows a relatively smooth curve through this section. However, when forcing the use of "Single-Tasking" option, results obtained from the NI system are corrected. NI now accurately matches the oscillations seen in the Simulink results (Figure 13c). More importantly, NI agrees with Simulink for the entire test, eliminating the hiccups or checkmarks seen in the results obtained from the NI system using the "Auto" tasking mode (Figure 13b).



(a)

(b)

(c)

Figure 13: HPC Surge Margin vs. Time – Comparison of NI, dSPACE, and xPC to native Simulink for a constant 15 kW HP load with a 74.4 kW step LP load.

CONCLUSION

Transient propulsion and power system modeling has been investigated using a Simulation Only configuration and a HIL configuration with real-time simulation platforms from dSPACE, National Instruments, and MathWorks. Various experiments were performed using the LP generator as the hardware component in the loop. Significant non-linear, transient behavior occurred when the power loads were applied and removed. These events cannot be predicted using traditional “cycle deck analysis” models. These transients could result in problems such as compressor stall, making it vital that transient events are modeled and that those models be exercised in integrated system analysis.

Excellent agreement was shown between the HIL and Simulation Only model results. These results are consistent with the results seen previously and further validate the capability of using HIL in propulsion and power experiments[7]. However, significant differences were initially seen between the results produced by the real-time systems, specifically during transients. While results obtained from the dSPACE and xPC real-time systems are consistently in good agreement with results obtained from the same model running in native Simulink, results obtained from the National Instruments system were not in agreement. Once a workaround provided by National Instruments’ technical support was implemented, dSPACE, xPC, and National Instruments were all in agreement with the results obtained from running the same model in native Simulink. These results show that each real-time operating system can be configured to accurately run transient Simulink models for Simulation Only or for Hardware-in-the-Loop studies.

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